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Late Holocene environmental dynamics, vegetation history, human impact, and climate change in the ancient *Literna Palus* (Lago Patria; Campania, Italy)

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ABSTRACT

A new late-Holocene high-resolution pollen record is presented from Lago Patria with the aim of investigating past vegetation and environmental dynamics in a still under-investigated coastal sector of the Campania region (Italy). Our results show the evolution of a mixed deciduous and evergreen oak-dominated lowland forest, rich in both xeric and mesic woody taxa, under the influence of climate, human impact, geomorphic processes and their interplay. Between 4800 and 2800 cal BP, the pollen record highlights only slight vegetation changes, featured by a modest forest decline around 4200 cal BP, consistent with the deforestation pattern produced by the 4.2 ka arid climate event in southern and central Italy. This event was followed, between 3900 and 3300 cal BP, by a forest recovery with a remarkable development of mesic trees, notably *Fagus*, influenced by wet climate conditions. While Bronze Age and Iron Age settlements are missing from this coastal area, which suggests a marginal role of human activity in the environmental changes of this period, the continuous presence of anthropogenic pollen indicators in the pollen record stimulates new archeological investigations. Between 2800 and 2200 cal BP, the area experienced successive domination by Greek, Etruscan, Italic and Roman populations, culminating with the foundation and expansion of cities like Cumae, Capua, and Dicearchia/Puteoli, which determined major impact on the natural forest through intense agricultural practices. After a sedimentation hiatus between 2200 and 180 BP, the pollen record documents a few tens of years, during the Bourbon domination, when the vegetational landscape, characterized by cultivations and pasturelands, appears almost completely treeless. Pollen and other palynomorphs of aquatic taxa evidence a change from freshwater to brackish conditions, consistent with the transition from cat's eye freshwater ponds to open lagoon.

1. Introduction

Mediterranean coasts are projected as one of the most vulnerable areas to climatic and anthropogenic changes (Santos et al., 2014), mainly due to the ever-increasing sea level and human population (Weisse et al., 2014; Neumann et al., 2015). Consequently, the natural estuarine and coastal ecosystems, which are extremely valuable biodiversity hot-spots, are experiencing a loss rate much higher than any other ecosystem on the planet (Pendleton et al., 2012). This process is especially worrying in some areas of the central Mediterranean (Spencer et al., 2016), such as the Venice and Orbetello lagoons, as well as the Volturno coastal area, where the risk of natural ecosystem loss is extremely high (Lambeck et al., 2011). However, the current environmental setting, when compared with the long-term natural and human-induced processes experienced by the coasts of the central Mediterranean since the middle Holocene, appears just as a snapshot within a multimillennial history of environmental instability. Many paleoenvironmental and archeological studies provide outstanding examples of long-lasting processes of natural ecosystems loss and recovery, related to the combined action of human activity, climate change, and geomorphic processes, which cannot be disregarded when analyzing the current vulnerability of the central Mediterranean coasts (Di Rita and Magri, 2012). Since the rise of agriculturally based societies in the Neolithic and the associated population expansion, humans have determined a progressive depletion of the coastal biotic and abiotic resources in many sites of the central Mediterranean (Colombaroli et al., 2007; Tinner et al., 2009; Bellini et al., 2009; Calò et al., 2012).

The number of pollen records in coastal sites of the central Mediterranean has much increased in the last two decades (Di Rita and Magri, 2012 and reference therein). These records are particularly effective in the detection of environmental changes produced by millennial and sub-millennial climate oscillations (Di Rita, 2013; Calo et al., 2013; Kaniewski et al., 2016), and by long-term process of land use conversion

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related to human activities (Noti et al., 2009; Di Rita and Magri, 2009; Currás et al., 2017; Russo Ermolli et al., 2018). Pollen records contribute to the definition of the effects of the relative sea level changes in coastal ecosystems, during both the Pleistocene/Holocene transition (Di Rita et al., 2015) and the Holocene (Poher et al., 2017; Di Rita et al., 2010; Melis et al., 2017) and provide paradigmatic examples of ecological dynamics associated with the ongoing sea level rise. In some regions, such as Sardinia and Apulia, coastal pollen records represent the only source of information on vegetation history (Caroli and Caldara, 2007; Di Rita et al., 2011; Beffa et al., 2016).

Despite the intrinsic potential of this methodology, coastal sites are not particularly appealing to palynologists, mostly due to: a) Severe pollen deterioration in sandy sediments, often leading to the loss of many pollen types and the selective preservation of the most resistant ones; b) Likely occurrence of stratigraphic gaps, often related to lowering in the water table of coastal basins and consequent desiccation, which determines hiatuses in pollen records; c) Uncertainty in ^{14}C age determinations, mostly due to difficult assessment of the carbon supply in transitional marine/continental environments, especially when dating is conducted on bulk material.

In this study we present a new high-resolution pollen record from a coastal core, drilled in the sediments of the Lago Patria, the ancient *Literna Palus*, ca. 13 km south of the mouth of the Volturno River. Lago Patria (40°56′N, 14°02′E) is a mesohaline coastal lagoon, ca. 2 km long, and 1.5 km wide, with an average water depth of 1.5 m, located in the southwestern sector of the Campania plain (South Italy) (Fig. 1). The aim of our research is to:

- Add new insights into coastal vegetation dynamics in coastal areas of the central Mediterranean from a still under-investigated region
- Define the impact of climate vs human activity on an estuarine ecosystem, close to an historically populated area
- Detect past ecological changes in the aquatic environment, through selected aquatic non-pollen palynomorphs (NPPs)

2. Geological setting

The present-day water body of Lago Patria occupies the southernmost part of a back-barrier depression of the Volturno delta plain within the Campania Plain. This depression lies at an elevation between 0 and 2 m with respect to the present sea-level (Fig. 1) and represents a man-modified remnant of a larger lagoonal area that evolved during the last 4.5 years within an alluvial delta system at the mouth of the Volturno River (Amorosi et al., 2012; Sacchi et al., 2014a).

The Campania plain inland, along with the Gaeta bay offshore, developed during the Pleistocene as a major NE-SE trending coastal basin in response to left-lateral transtensional tectonics that took place along the Eastern Tyrrhenian margin (Mariani and Prato, 1988; Oldow et al., 1993; Sacchi et al., 1994; Ferranti et al., 1996; Milia et al., 2003). Since Mid–Late Pleistocene, extension was accompanied by the onset of an intense volcanism that developed in several places across the continental margin (Cassignol and Gillot, 1982; Di Vito et al., 1999). At ca. 39 ka the entire Campania Plain was covered by thick deposits of a highly explosive ignimbrite eruption, known as Campania Ignimbrite (CI) (Barberi

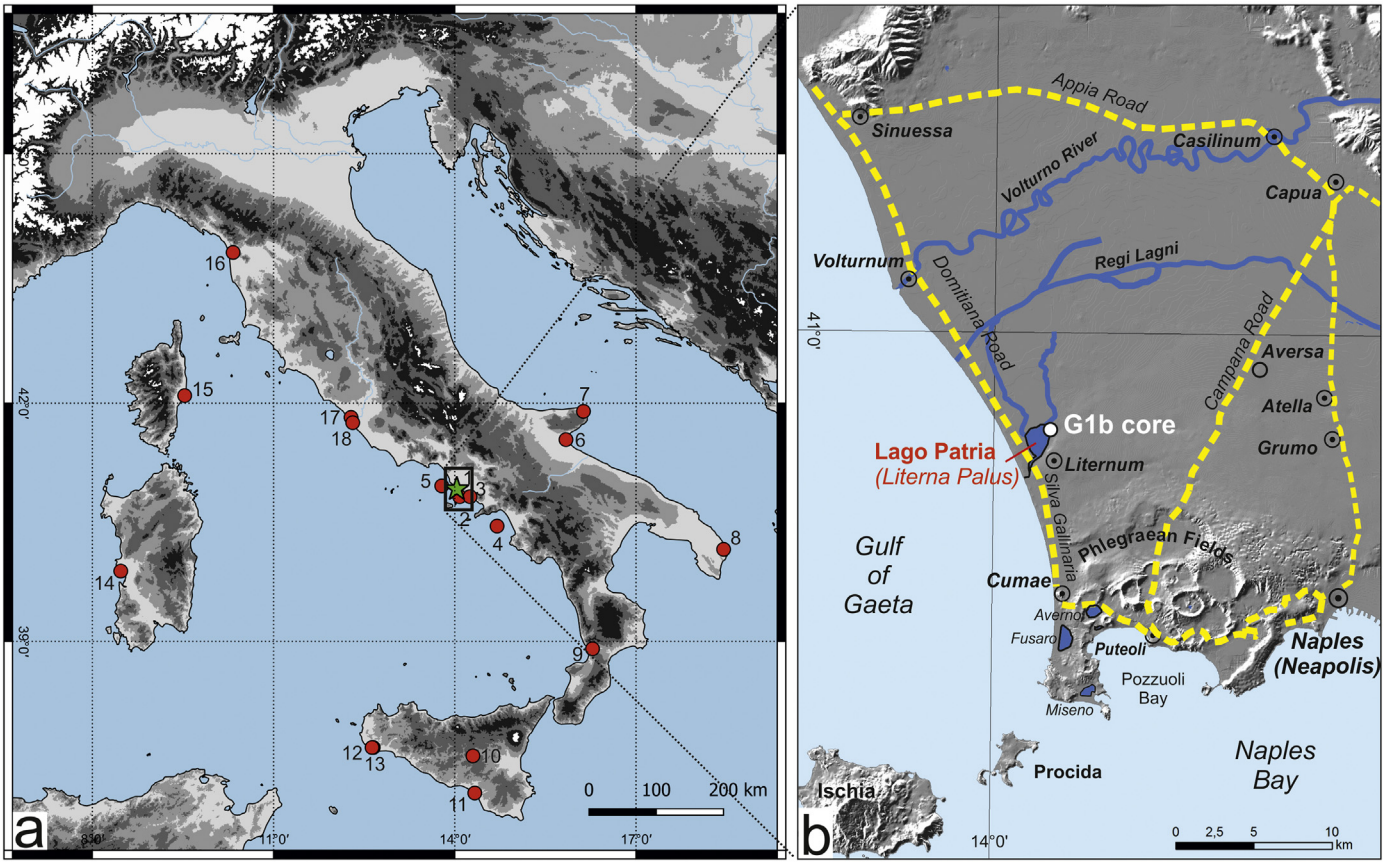

Fig. 1. (a): Location map of the pollen sites mentioned or cited in the discussion: 1. Lago Patria; 2. Lago d'Averno (Grüger and Thulin, 1998); 3. Neapolis harbor (Allevato et al., 2010, 2016; Russo Ermolli et al., 2014); 4. C106 (Russo Ermolli and di Pasquale, 2002); 5. Gulf of Gaeta (Margaritelli et al., 2016; Di Rita et al., 2018a); 6. Lago Salso (Di Rita et al., 2011); 7. Lago Battaglia (Caroli and Caldara, 2007); 8. Lago Alimini Piccolo (Di Rita and Magri, 2009); 9. Sant'Eufemia (Russo Ermolli et al., 2018); 10. Lago di Pergusa (Sadori and Narcisi, 2001); 11. Biviere di Gela (Noti et al., 2009); 12. Gorgo Basso (Tinner et al., 2009); 13. Lago Preola (Calò et al., 2012); 14. Mistras (Di Rita and Melis, 2013); 15. Aleria Del Sale (Currás et al., 2017); 16. Massaciuccoli (Colombaroli et al., 2007); 17. Lingua d'Oca-Interporto (Di Rita et al., 2010); 18. Ostia C5 (Bellotti et al., 2011). (b): map of the study area including the location of: Lago Patria, the study core G1b, the hydrographic grids of the main rivers, and the archeological sites of the area. Ancient roads are reported in yellow dashed lines.

et al., 1978; Di Girolamo et al., 1984; De Vivo et al., 2001; Rolandi et al., 2003). Another eruption, dated at ca. 15 ka, caused the deposition of the Neapolitan Yellow Tuff (NYT) that is primarily exposed in the area of Phlegraean Fields (Rosi and Sbrana, 1987; Scarpati et al., 1993; Deino et al., 2004; Sacchi et al., 2014b).

In the course of the latest Quaternary the continental margin was largely exposed to the subaerial domain as a consequence of the eustatic sea level fall occurred between ca. 125 and 18 ka BP. During this period, the area was characterized by the development of an incised valley system engraved by the paleo-Volturno river onto a Mesozoic carbonate bedrock mantled by volcaniclastic deposits originated from the Campania Ignimbrite eruption (39 ka BP; Rosi and Sbrana, 1987; De Vivo et al., 2001; Fitzsimmons et al., 2013; De Natale et al., 2016) and associated andosols, which represent the substrate of the modern alluvial plain succession.

The postglacial transgression following 15 ka BP marked the onset of a rapid back stepping of the coastal marine sequence, followed by late-stage aggradation and the formation of the present-day Volturno delta plain at ca. 5 ka BP. Between 4.8 and 4.5 ka BP a coastal barrier system started to form off the mouth of the Volturno River. At same time, in the back-barrier region a large wetland associated with an open coastal lagoon system began to develop as an integral component of the Volturno delta plain (Amorosi et al., 2012; Sacchi et al., 2014a).

The ancient lagoonal area reached a maximum extent of more than 20 km^2 (more than six times the present-day surface of Lago Patria) between 3.6 and 2.5 ka BP. The presence of a wide lagoon was also documented by the Greek geographer Strabo, who reported that a wide north–south embayment existed from the Sinuessa to Capo Miseno (Biraschi, 1988).

3. Early human settlements, vegetation and climate

Despite the active volcanism in historic and prehistoric times, human presence in Campania is documented since the Paleolithic. During the Eneolithic, traces of cultivated fields and plowing have been identified just below the pyroclastic materials of the Agnano-Montespina eruption (4.42 ka BP), but no stable settlements have been recognized (Nava et al., 2007; Saccoccio et al., 2013). Several Bronze Age sites have been studied north of Naples and in the volcanic area of Somma-Vesuvius and Plegraean Fields (Albore Livadie et al., 2005; Laforgia et al., 2009; Saccoccio et al., 2013; Di Vito et al., 2013). However, due to the occurrence of swampy and marshy areas, large part of the Volturno coastal plain remained mostly uninhabited until the 4th century BCE. In fact, excluding some weapons deposits (Albore Livadie, 2007), the Bronze Age archeological finds are rare in the coastal plain, while the Iron Age settlements are completely missing (Nava et al., 2007). The first historical evidence of human settlement around Lago Patria was a colony of the Opici people, which dates back to the 9th century BCE. Starting from the 8th century BCE the coastal plain was colonized by the Greeks, and in the 6th century inland areas were occupied first by the Etruscans and then by other Italic populations, including Samnites and Osci. The Etruscans also controlled the coastal areas of the Gulf of Gaeta, where they built the town of Volturnum, located at the mouth of the Volturno River, in the territory occupied by an ancient Opici settlement. Volturnum became an important trade point along the road to Capua, another major Etruscan city. In the second half of the 4th century BCE, the region was occupied by the Romans, who considered Campania the most prosperous region of the Italian Peninsula (*Campania Felix*), mostly because of the fertility of its soils. In 194 BCE, Volturnum became a Roman colony with the main purpose of controlling the lower course of the Volturno River. Another important Roman colony, named Liternum, was built on a rocky basement on the southern side of Lago Patria. Liternum was chosen as a residence by Scipio Africanus, who died there in 183 BCE. In Imperial times, the inland area of the Liternum territory was exploited for olive, grape and cereals cultivation (Camodeca, 2010). Starting in the 6th century CE, the region was progressively occupied by the Lombards, and in the 11th century by the Normans. The 11th century also coincided with a phase of expansion of Benedictine monasticism in Campania. A large marsh south of the Volturno river mouth was controlled by the Benedictine Monastery of San Lorenzo d'Aversa. From the 13th to the 16th century CE the region was under the rule of the Angevin and Aragonese, followed by the Spanish domination until 1734. Geographic maps produced between 1620 and 1711 still indicate the occurrence of a large lagoonal area that developed parallel to the old coastline, mostly north of the modern Lago Patria, and received a freshwater input by the Clanio River tributary.

Lago Patria reached its present shape and size following a major land reclamation of the vast lagoon characterizing the southern sector of the Volturno lower plain. This systematic drying of the coastal plain was conducted at various stages. It started during the Spanish viceroyalty (1504–1707), continued during the Bourbon domination and was concluded by the Italian government between 1939 and 1942.

The Campania region has a typical Mediterranean climate, with precipitations of up to 1200 mm on elevated regions and an average of ca. 850 mm along the coastal plains. The mean annual temperature correspondingly varies between 9 °C and 16 °C. Both climate and the modern vegetation of the Gulf of Gaeta borderlands, including Lago Patria, appear to be strongly related to the inland orographic complexity and the vicinity of the sea (Filesi et al., 2010). Sclerophyllous shrublands and *Quercus ilex* woodlands generally dominate the coastal promontories and the south-facing slopes at low altitudes (ca. 0–600 m), while mixed evergreen/deciduous and deciduous forest formations are more frequent at higher altitudes, favored by orographic humidity. Conifer forests have a patchy distribution in the area. They especially border the Gulf of Gaeta, where stands of *Pinus pinea*, *Pinus halepensis* and *Pinus pinaster* were planted along the coast since 1955, when a Nature Reserve was established at the mouth of the Volturno River, currently designated as a Ramsar Site. Pine formations are also frequent in the slopes of Mount Vesuvius. The natural lowland forests have been substituted by both agricultural areas, characterized by arable lands and permanent orchards, and urban areas.

4. Materials and methods

The pollen record documented in this study was acquired from borehole G1b, drilled on the NE shore of Lago Patria (40° 56′ 39,38″ N, 14° 02′ 19,71″ E)(Sacchi et al., 2014a).The sampled successions represented by a transgressive-regressive unit composed of isolated (cats' eye) pond and back-barrier brakish lagoon deposits overlying a volcanic substratum (7.60–6.35 m), passing toward the top to open lagoon deposits (6.35–5.40 m), and terminating with restricted brakish lagoon deposits (5.40–4.00 m). The study sequence is overlain by reworked material forming the modern embankment of Lago Patria since the Bourbon domination of the Campania region (Fig. 2).

The chronology of the core is based on 5 ^{14}C AMS dates obtained from mollusk shells and organic-rich layers (Sacchi et al., 2014a) (Fig. 2 and Table 1). The measurements were performed with a system based on a tandem accelerator with a maximum terminal voltage of 3 MV and a ripple better than 1 kV FWHM (for further information see also Sacchi et al., 2014a). Samples were pre-treated in accordance with the procedures outlined in Paolillo and Giudicianni (2009). The Age-Depth model was based on a cubic spline method between the three most ancient calibrated dates, using the software Clam 2.2 (Blaauw, 2010) (Fig. 2).

Pollen analysis was carried out on 49 samples, 46 of which collected between 768 and 232 cm depth. The remaining 3 samples were collected between 1060 and 768 cm to test for the presence of pollen. The first 232 cm of the core were not analyzed due to the occurrence of coarse-grained sediments of artificial embankments in most of the interval. Pollen extraction followed the standard procedures summarized in Magri and Di Rita (2015); the samples were chemically treated with

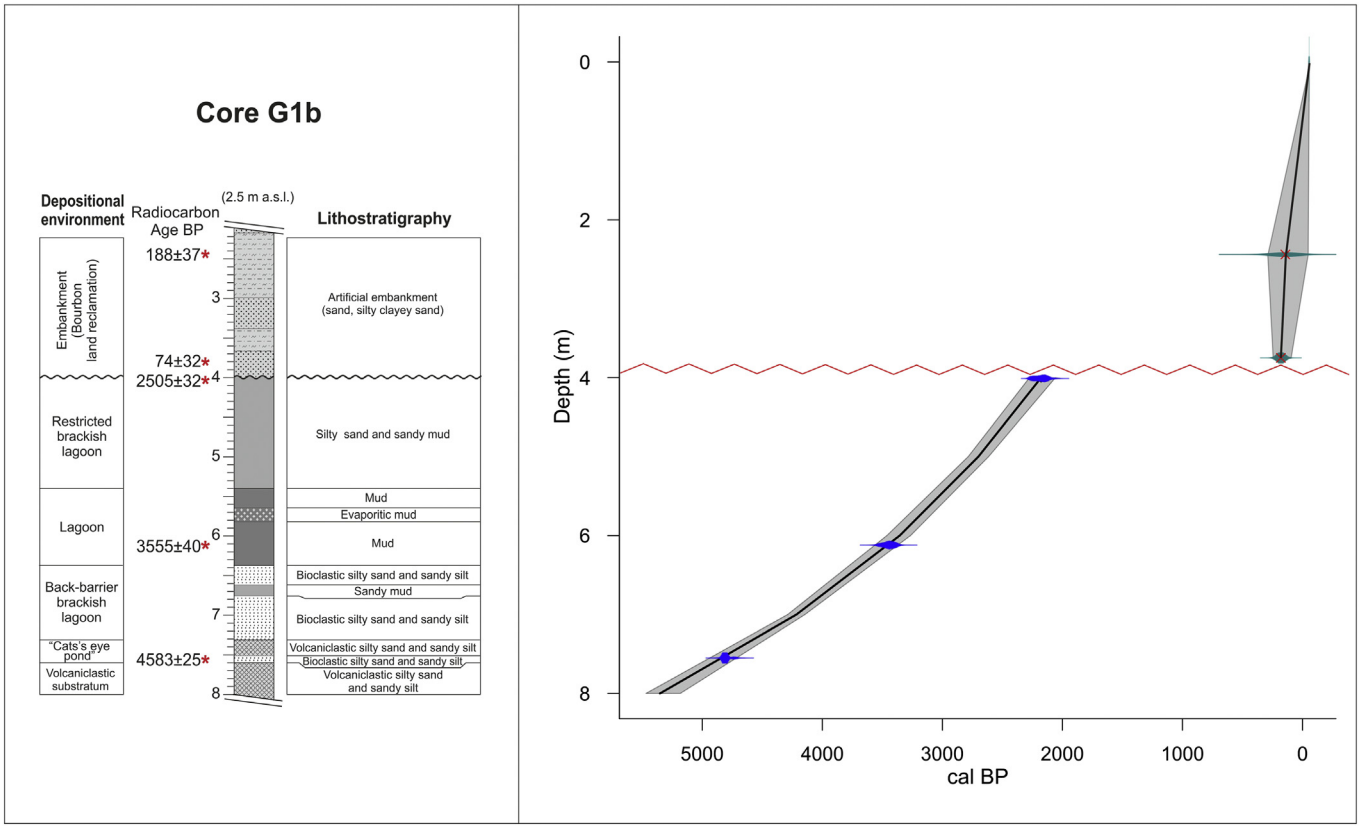

Fig. 2. Stratigraphic column and age-depth model of core G1b. Lithostratigraphy and facies are from Sacchi et al., 2014a. Age-depth model of coreG1b was produced using the software Clam 2.2 (Blaauw, 2010).

HCl (37%), HF (40%) and NaOH (10%). Pollen concentration values were estimated by adding *Lycopodium* tablets to known weights of sediment. Pollen grains were identified by means of a light microscope at 400 and 640 magnifications, with the help of pollen morphology atlases (e.g., Reille, 1992; Beug, 2004). The main percentage sum was based on terrestrial pollen excluding pollen of aquatics, spores of ferns and other NPPs. The software Psimpoll 4.27 (Bennett, 2009) was used to plot the percentage pollen diagrams and to subdivide them into 7 local pollen zones, numbered from the base upwards and prefixed by the site abbreviation PAT. Microcharcoal analysis of the sequence was carried out to reconstruct the fire history of the area. The analysis followed the procedures described by Clark (1982). A number of 150 microscope fields were counted for each pollen sample. Microcharcoals smaller than 5 μm were excluded from the sum. *Lycopodium* spores were used to estimate microcharcoal concentrations.

5. Results

5.1. Age depth model

The age depth model of drill core G1b shows that the pollen record interval between 761 and 405 cm was deposited in 2640 years, with an average sediment accumulation rate of ca. 0.135 cm/year. The radiocarbon dates at 4.01 and 3.75 m (Table 1) point to a hiatus in sedimentation, indicated also by an abrupt change in lithology, from sandy silts and clayey silts to mostly sandy artificial embankments. This reflects also a major environmental change, documented by mollusk assemblages. The uppermost 4 m of the core were accumulated in a few centuries, as result of reclamation works since the Bourbon time (Sacchi et al., 2014a).

5.2. Pollen analysis

The pollen sequence from Lago Patria reveals a high floristic richness. On the whole, 112 taxa have been identified, including pollen, spores and other non-pollen palynomorphs. Pollen preservation is generally good, and the value of indeterminable grains exceeds 5% only in 5 samples. The total pollen concentration is very heterogeneous along the sequence, varying from 950 to 40,000 grains/g. The mean pollen count was ca. 250 of terrestrial pollen grains per sample. *Alnus* was excluded from the main sum, because it commonly lives in estuarine floodplain woods, where it is frequently over-represented mostly due to its very high pollen production.

The results of pollen analysis are presented as: 1) a detailed percentage diagram, including most of the single pollen taxa and the Arboreal Pollen (AP)/Non Arboreal Pollen (NAP) percentages plotted against

Table 1
Radiocarbon dates used to calculate the age-depth model. The IntCal13 and Marine13 datasets were used to calibrate the radiocarbon dates (Reimer et al., 2013).

Sample	Depth (m)	Material dated	Radiocarbon age (yr BP)	Calibration method	Calibrated ages 2 sigma range (cal BP)
G1bis 3/9	2.44	Sediment	188 ± 37	IntCal 13	−72-358
G1bis 4/35	3.75	Sediment	74 ± 32	IntCal 13	114–246
G1bis 5/41	4.01	Bivalve	2505 ± 32	Marine 13	2078–2290
G1bis 7/84	6.12	Bivalves and gasteropods	3555 ± 40	Marine 13	3352–3550
G1bis 9/113	7.55	Bivalve	4583 ± 25	Marine 13	4710–4854

depth (Fig. 3); 2) a synthetic pollen diagram plotted against age (Fig. 4), including: cumulative percentages of conifers, riparian trees, deciduous trees, evergreen trees and shrubs, broadleaved woody taxa (the sum of deciduous and evergreen trees and shrubs), anthropogenic trees, anthropogenic herbs, selected records of NPPs, microcharcoal, and total pollen concentrations; 3) a diagram of pollen concentrations of the main taxa (Fig. 5).

Local pollen zones can be schematized as follows:

Zone PAT-1 (761–733 cm; 4870–4580 cal BP): the forest cover (AP > 87%) was composed of mixed deciduous and evergreen broadleaved taxa (84%), dominated by *Quercus ilex* type (35%) and deciduous *Quercus robur* type (15%), along with *Ostrya/Carpinus oriantalis* (13%) and *Fagus* (12%). They are accompanied by several woody taxa with frequencies never exceeding 5%: *Quercus cerris* type, *Carpinus betulus*, Ericaceae, *Pinus*, *Corylus*, and Ericaceae. *Abies* is continuously recorded. Cyperaceae (5%) and Poaceae (5%) are the main herbaceous taxa. Aquatics are mainly represented by *Myriophyllum spicatum* (5%) and *Myriophyllum alterniflorum* (2%). *Pediastrum* (58%) and Botryococcaceae (14%), and *Filinia* eggs, characterize NPPs.

Zone PAT-2 (733-664 m; 4580–3910 cal BP): a forest decline (AP 65%), culminating around 4200 cal BP, was mainly related to a

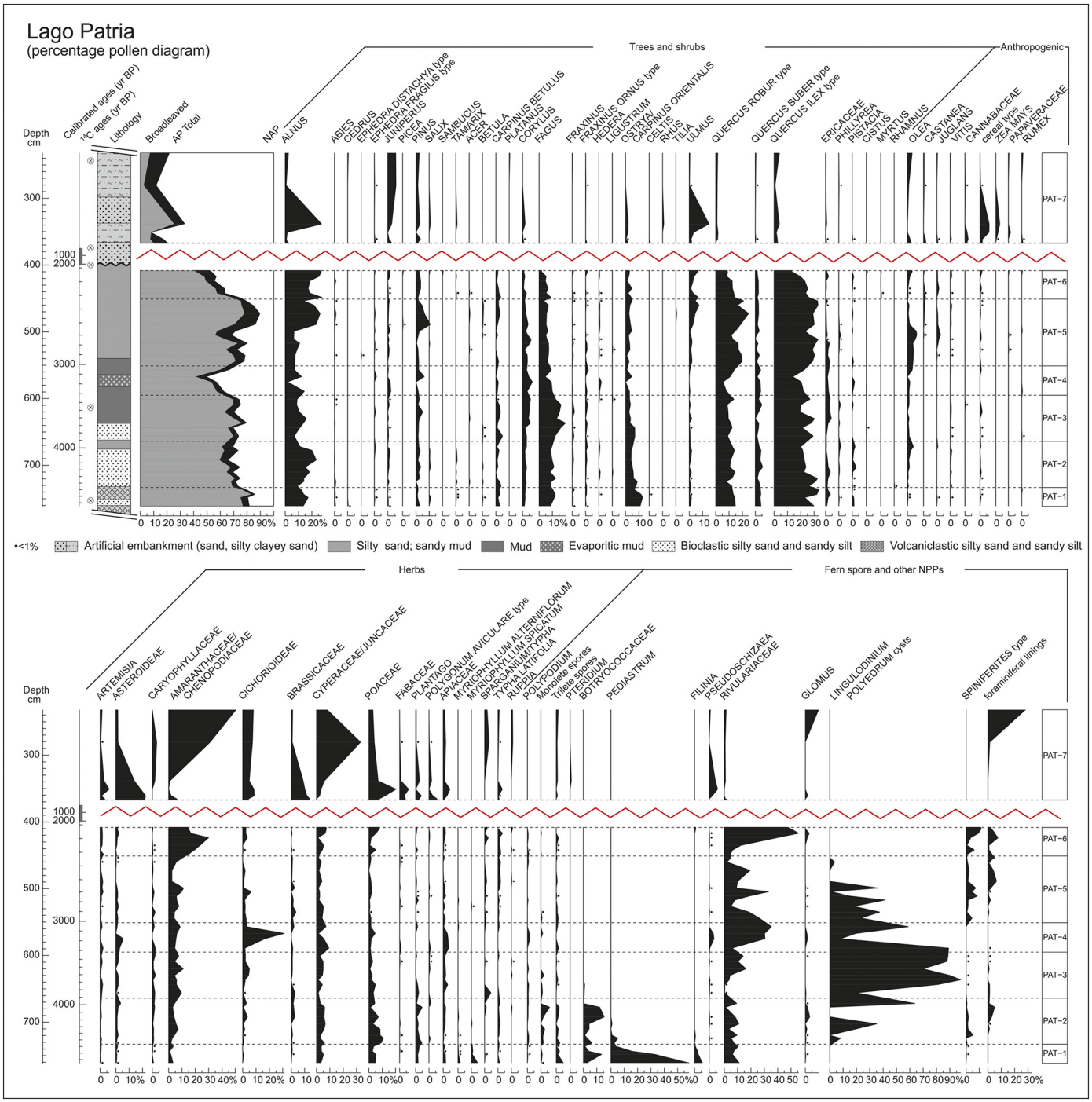

Fig. 3. Pollen percentage diagram from Lago Patria (core G1b).

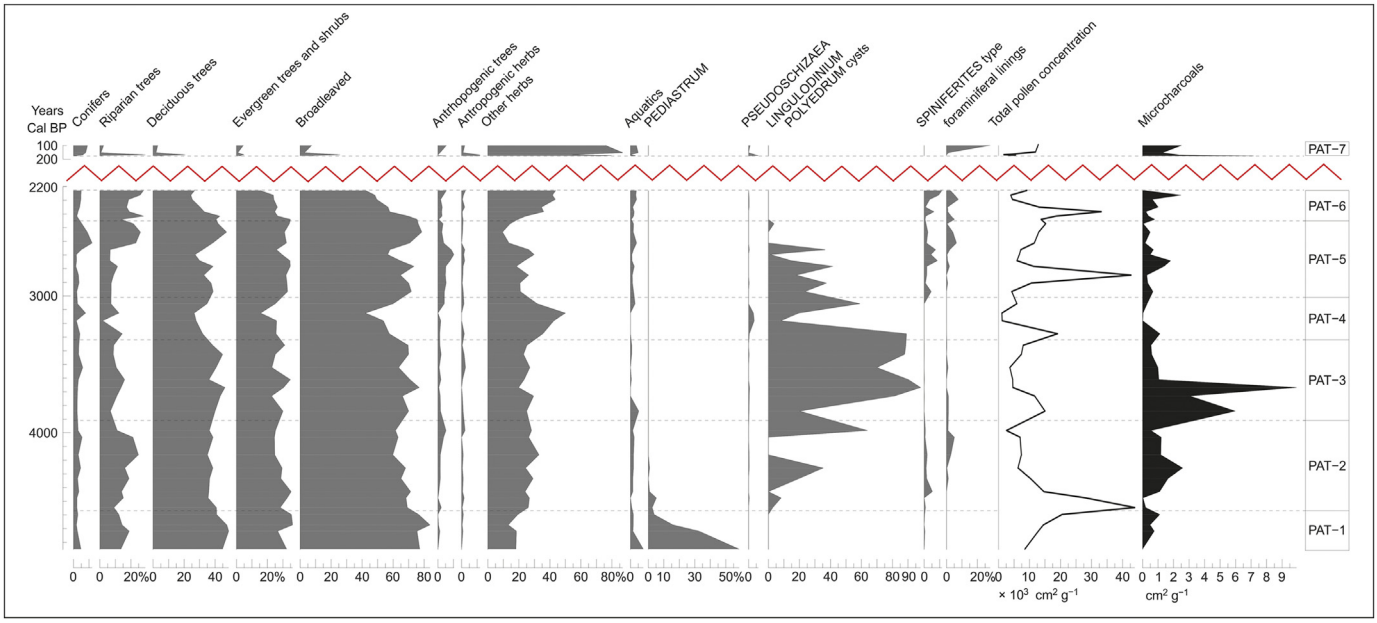

Fig. 4. Synthetic pollen diagram plotted against the age from Lago Patria (core G1b).

decrease in broadleaved taxa (60%). It was accompanied by a significant increase in herbaceous taxa (35%), Poaceae (11%), Amaranthaceae/Chenopodiaceae (7%), *Plantago* (5%), Cichorioideae (4%), and Apiaceae (2%) being the most abundant. Aquatics decline along with freshwater NPPs; they are replaced by dinoflagellate cysts (*Lingulodinium polyedrum* type and *Spiniferites* type) (Fig. 6) and foraminiferal linings, showing a significant increase along the zone.

Zone PAT-3 (664–595 m; 3910–3320 cal BP): a new increase in broadleaved taxa is favored by a significant rise in *Fagus* (20%) and *Quercus ilex* type (18%). Other tree taxa increase, including *Ostrya/Carpinus orientalis* (10%), *Carpinus* (6%), and *Corylus* (6%), among deciduous trees, and Ericaceae, among evergreen woody taxa. AP percentages show a clear increase only in the central part of the zone. Amaranthaceae/Chenopodiaceae increases up to 10%. The dinoflagellate cyst of *Lingulodinium polyedrum* (Fig. 6) shows its highest frequencies in the sequence.

Zone PAT-4 (595–551 cm; 3320–3010 cal BP): the forest vegetation shows an abrupt decline, as indicated by AP percentages dropping to 43% around 3100 cal BP. This corresponds with a lithological change consistent with the development of an evaporitic layer rich in gypsum. Almost all the trees decline in the middle part of the zone, opposed to a dramatic increase in Cichorioideae (32%). This interval records a strong decrease in dinocysts, an increase in Rivulariaceae, and occurrences of *Pseudoschizaea* and *Glomus*.

Zone PAT-5 (551–451 cm; 3010–2450 cal BP): a considerable increase in trees (max AP 90%) is largely imputable to a marked increase in both *Quercus ilex* type and *Quercus robur* type (33% and 25% respectively) and *Pinus* (11%), especially in the upper part of the zone, accompanied by *Ulmus* (7%) and *Carpinus betulus* (3%), as well as *Olea* (6%) and *Juglans* (2%) among anthropogenic trees. A temporary forest decline in the middle part of the zone corresponds to an increase in Amaranthaceae/Chenopodiaceae, Cichorioideae, Poaceae, and anthropogenic indicators, including the anthropogenic trees. The NPPs are represented by *Lingulodinium polyedrum*, *Spiniferites* type, Rivulariaceae, and foraminiferal linings.

Zone PAT-6 (451–405 cm; 2450–2230 cal BP): a new marked drop in forest vegetation causes AP% to decrease to 53%. Anthropogenic trees show a rather continuous record with a slight increase in the upper part of the zone. Amaranthaceae/Chenopodiaceae and Poaceae increase in this interval. Among NPPs, Rivulariaceae and *Spiniferites* strongly increase; foraminiferal linings keep high frequencies, while *Lingulodinium polyedrum* disappears.

Zone PAT-7 (365.5–232 cm; ca. 180–140 cal BP): AP percentages (8–33%) indicate a frankly open landscape. A clear increase in the percentage and diversity of herbaceous taxa is recorded, including various anthropogenic indicators, such as Cannabaceae, *Zea mays*, cereals, *Mercurialis* type and Papaveraceae. The pollen record ends with a peak in foraminiferal linings and *Glomus*.

6. Discussion

The pollen record from Lago Patria provides new information on the late Holocene vegetation history of Campania, complementing pollen records from the Gulf of Salerno, spanning the last 35 ka (Russo Ermolli and di Pasquale, 2002), the Gulf of Gaeta (ca. 22 km from Lago Patria; late Holocene) (Margaritelli et al., 2016; Di Rita et al., 2018a, 2018b), Lago d'Averno (15 km West of Naples; 6th century BCE to 6th century CE) (Grüger and Thulin, 1998), and a pollen/wood analysis at the Neapolis harbor (2th century BCE–5th century CE) (Allevato et al., 2010, 2016; Russo Ermolli et al., 2014).

The pollen record from Lago Patria contributes to fill a gap of knowledge on the paleovegetational changes in the coastal sector of the Campania Plain, by focusing on a time-interval characterized by intense human frequentation and major volcanic eruptions, which strongly affected the ecosystem stability and human peopling of the investigated region.

The main paleoenvironmental changes are also discussed with respect to other pollen records reported from central and southern Italy (Fig. 1), taking into account the marked geographical and ecological differences among regions. The human impact on vegetation has been interpreted considering both the history of the human frequentation in the area, as attested by archeological sites and historical documents, along with paleobotanical information from the regional literature.

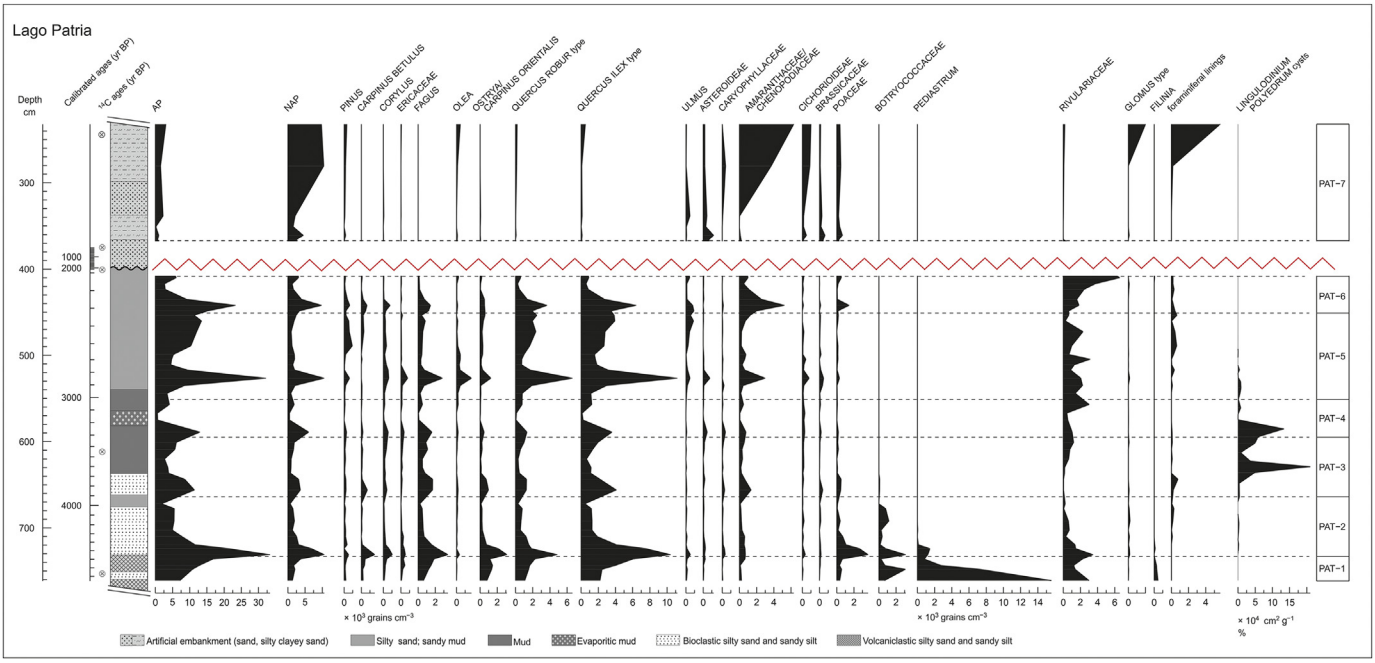

Fig. 5. Pollen concentrations diagram of selected taxa from Lago Patria (core G1b).

6.1. 4870–4580 cal BP (761–733 cm)

This time interval is dominated by deciduous trees, mostly represented by *Quercus*, *Ostrya/Carpinus orientalis*, *Carpinus betulus* and *Ulmus*, although the evergreen vegetation was also well represented, being *Quercus ilex* type the main pollen taxon (Figs. 3 and 4). This mixed deciduous and evergreen oak-dominated lowland forest, whose remnants are commonly preserved in coastal natural parks, was probably widespread along the Tyrrhenian coast of Italy since the early Holocene (Magri and Di Rita, 2015; Di Rita et al., 2015; Doorenbosch and Field, 2018).Today, a paradigmatic example is found in the Circeo National Park, where a protected woodland, mainly composed of *Quercus robur*, *Quercus cerris*, *Quercus frainetto*, *Quercus ilex*, *Carpinus orientalis*, *Carpinus betulus*, *Fraxinus ornus*, *Fraxinus angustifolia*, *Erica arborea*, and *Arbutus unedo*, is confined in a lowland area immediately behind the dunes and coastal lakes of Sabaudia.

The pollen record from a marine core (C106) collected in the Bay of Salerno confirms the existence of mixed deciduous and evergreen woodlands in Southern Campania, dominated by deciduous oaks (Russo Ermolli and di Pasquale, 2002). Conversely, in the pollen record from the Gulf of Gaeta the mixed woodlands were mostly characterized by evergreen oaks, reflecting their dominance in the coastal sectors of northern Campania and southern Lazio. The coastal pollen sites from Apulia, Sicily and Sardinia, mostly located within the evergreen vegetation belt, testify for widespread Mediterranean *maquis* formations, composed of evergreen *Quercus*, *Pistacia* and Ericaceae (Caroli and Caldara, 2007; Di Rita and Magri, 2009; Noti et al., 2009; Tinner et al., 2009; Calò et al., 2012; Di Rita and Melis, 2013).

Of note is also the significant frequency of montane mesophilous trees *Fagus* and *Abies* (Figs. 3 and 5). At present, *Fagus sylvatica* is the main canopy species in zonal forest communities between 900 and 2000 m in the Apennines, where it reaches the tree-line. Considering the position of Lago Patria with respect to the shoreline, high frequencies of *Fagus* point to extra-zonal populations at low elevation in this sector of Campania. Similarly, the continuous record of *Abies* is an evidence for the vicinity of fir populations. Wood remains dated between

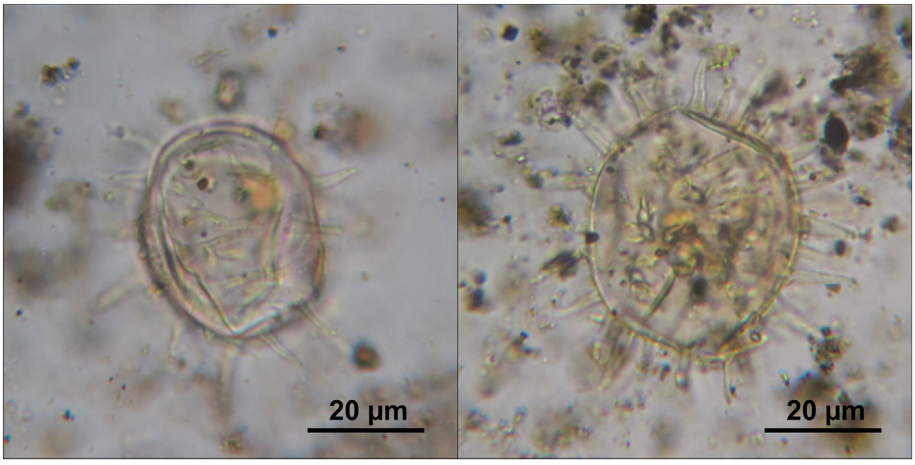

Fig. 6. Two cysts of the dinoflagellate *Lingulodinium polyedrum* found in the sample at 636.5 cm.

the 17th and 16th BCE from the settlement of Longola-Poggiomarino (Di Pasquale et al., 2014 and references therein), not far from Mt. Vesuvius, prove that *Abies* lived on the volcanic slopes of Campania at least up to the late Holocene at an elevation lower than it is today.

Pollen evidence of human activities is quite limited in this phase. Low frequencies of cereal-type point to cultivation in the region, while single record of *Juglans* is consistent with the scanty finds reported in several sites from southern Italy between 6000 and 3000 cal BP, thus supporting the existence of sporadic native populations (Di Rita et al., 2011; Mercuri et al., 2013).

The aquatic environment of Lago Patria was characterized by freshwater conditions, as revealed by *Myriophyllum spicatum* and *Myriophyllum alterniflorum*, freshwater *Pediastrum* and eggs of the rotifer *Filinia* (Fig. 3). It is worth noting that remarkably high concentrations of *Pediastrum* (Fig. 5), consistent with major and prolonged algal blooms, may reflect an eutrophication phase of the basin, which appeared as a cat's eye pond system at that time (Sacchi et al., 2014a).

6.2. 4580–3910 cal BP (733–664 cm)

A progressive forest decline, culminating around 4200 cal BP, involved the broadleaved vegetation (Figs. 3 and 4). A similar and coeval vegetation opening, reported from the Gulf of Gaeta, was related to the wider forest decline pattern occurred in the central Mediterranean as a possible consequence of the so called "4.2 ka BP climate event". This vegetation change documented in many pollen records south of 43°N (Sadori and Narcisi, 2001; Di Rita and Magri, 2009; Noti et al., 2009; Tinner et al., 2009; Di Rita et al., 2011; Desprat et al., 2013), may have been influenced by a complex and still under-investigated interplay between the North Atlantic Oscillation and subtropical climate modes (Magny et al., 2013; Zanchetta et al., 2016; Di Rita et al., 2018a, 2018b), which likely caused a general decrease in precipitations, mainly in central-southern Italy. A climate change was testified also by the $\delta^{18}O_{G.ruber}$ signal of the Gaeta core, pointing to a local decrease in temperature (Margaritelli et al., 2016), which probably affected also the coastal environments in the surroundings of Lago Patria.

Our pollen record shows peculiarities that cannot be neglected in the interpretation of this forest decline. The anthropogenic indicators, well represented by cereals, *Vitis*, *Olea*, and *Juglans*, accompanied by significant microcharcoal concentrations (Figs. 3 and 4), may suggest that human populations used fire in order to clear the forest and obtain new land for cultivation. An accurate analysis of the pollen record, however, reveals that a significant increase in anthropogenic indicators occurred only after the maximum opening of the forest at 4200 cal BP. Thus, we infer that human populations benefited from a natural vegetation opening, which produced suitable environmental conditions for the development of agro-pastoral activity (Magri, 1995). Moreover, the increase in *Olea*, paralleling the natural companion species *Pistacia* and *Phillyrea*, does not reflect cultivation (Russo Ermolli et al., 2018). Similarly, *Vitis* was parallel to *Alnus*, which is its main companion in the natural riparian vegetation. In other Holocene and Pleistocene pollen records the two taxa are contemporarily recorded with no evidence of human impact (Mariotti Lippi et al., 2007; Di Rita et al., 2010; Currás et al., 2017). The wild subspecies of *Vitis vinifera* was certainly present since the beginning of the Holocene in the wetlands of the alluvial coastal plains of southern Italy, where it was probably managed since the Bronze Age (Aiello et al., 2008; Di Pasquale and Russo Ermolli, 2010; Russo Ermolli et al., 2018). Despite olive and grape cultivation should be excluded in this phase, olive stones and grape pips retrieved in the early Bronze Age archeological site of Nola-Croce del Papa suggest that their fruits were used as food in the region (Albore Livadie et al., 2011). Hazelnuts and almonds were also used as semi-natural fruits, along with many other wild fruits such as acorns (Albore Livadie, 2007).

The Campania Plain was interested by an intense human frequentation during the early Bronze Age as documented by its conspicuous inland settlements (Albore Livadie et al., 2011), which exerted an intense land exploitation through extensive agricultural practices, stock-rearing activities and natural resource management (Albore Livadie, 2007). The Campania plain and the Vesuvius region offer several examples of inland settlements with remarkable skills in land use (e.g. Laforgia et al., 2009; Di Vito et al., 2013; Saccoccio et al., 2013). By contrast, in coastal areas the Bronze Age archeological finds are rare, and not attributable to any local settlement. Only some axes deposits, currently destroyed, were documented around Lago Patria and in a few coastal sites of northern Campania (Albore Livadie, 2007). This seems to conflict with the evidence of cereal cultivations from our pollen record, unless it represents plantations from the hinterlands. For example, in the site of Gricignano, 10 km away from Lago Patria, uninterrupted plowed surfaces and field systems of 60 ha featured by banks, gullies, and cart tracks was discovered, testifying for a remarkable and systematic landscape exploitation by farming activity, especially addressed to cereal cultivation (Saccoccio et al., 2013).

Between ca. 4500 and 4000 cal BP, the severe phase of volcanic activity characterized by Agnano-Montespina and Astroni eruptions from the Phlegraean Fields (Isaia et al., 2004; De Vita et al., 1999) and culminated with the huge explosive pyroclastic eruption called "Pomici di Avellino" from Mont Vesuvius, determined a strong impact in the human peopling of the region (Di Vito et al., 2013). Notably the latter eruption destroyed several Bronze Age settlements and the residents hastily abandoned the villages looking for new land (Passariello et al., 2009). One of the main hypothesis suggests an exodus toward the coasts of southern Lazio region (e.g. Bakels et al., 2015). In addition, the coastal areas of the Volturno floodplain potentially offered land to establish new villages, especially if we consider that a large portion of this region was not covered by massive pyroclastic products of the above-mentioned eruptions (Isaia et al., 2004; De Vita et al., 1999; Di Vito et al., 2009). However, possible unhealthy environmental conditions may have discouraged human populations to settle in this marshy area. In fact, the Volturno delta plain until the beginning of the 20th century hosted swamps and ponds associated with a high incidence of malaria (Ruberti and Vigliotti, 2017). These unhealthy conditions were reported also by ancient historians, including Livy. Nonetheless, the evidence of cereal cultivation and the increase in anthropogenic pollen indicators, especially around 4000 cal BP, encourages new archeological investigations to search for Bronze Age settlements in this coastal area.

As to fire activity, in our record it appears difficult to define the effects of fires on vegetation based on charcoal concentrations. Microcharcoal peaks are sometimes associated with forest decline, as in this interval, and sometimes to forest development, as in zone PAT-3, suggesting that there is no univocal relationship between fire and forest dynamics (Fig. 4). This may also depend on a possible enhancement of microcharcoal concentrations by charcoal originated from the Phlegraean Fields and Somma/Vesuvius volcanic eruptions. The Clanio River may have transported into the lake charcoal particles from areas affected by the pyroclastic fallouts, thus adding further complexity in the identification of man-induced fires.

The pollen record indicates a clear change in the aquatic environment of Lago Patria. The almost complete disappearance of *Myriophyllum*, along with *Pediastrum* and *Filinia*, opposed to the significant increase in both *Lingulodinium polyedrum* and *Spiniferites* type dinocysts, as well as in foraminiferal linings, point to a change from freshwater to brackish water conditions, related to a seawater input (Figs. 3–5). The mollusk assemblages also point to a brackish back-barrier lagoon (Sacchi et al., 2014a).

6.3. 3910–3320 cal BP (664–595 cm)

A new general forest development is revealed by an increase in broadleaved trees, mainly *Fagus*, *Ostrya/Carpinus orientalis*, *Carpinus*

betulus, and *Corylus*, among deciduous taxa, and *Quercus ilex* and Ericaceae, among the evergreen ones (Figs. 3–5). The significant rise of moist-loving trees suggests a climate change toward wetter conditions, while the parallel remarkable increase in evergreen Mediterranean trees suggests a warm climate. A forest expansion is recorded also in the Gulf of Gaeta, with high frequencies of deciduous trees and a remarkable and rapid recovery of evergreen trees, consistent with increasingly warm and wet conditions (Di Rita et al., 2018a, 2018b). The planktonic foraminifers analyzed in the same record confirm this climate change, indicating strong seasonality and continental runoff related to increased precipitations during late winter/earlyspring (e.g., Margaritelli et al., 2016). A general expansion of arboreal vegetation, especially evergreen taxa, is also observed in the record of many coastal and inland pollen sites, especially those affected by the 4.2 ka aridification process, as a result of a general increase in precipitation affecting a wide region in the south-central Mediterranean (Di Rita et al., 2018a and reference therein).

Fagus was particularly favored by the climate change of this phase. Its high frequencies appear to be consistent with the development of beech stands close to Lago Patria, possibly located on the slopes of the volcanic reliefs of the Phlegraean Fields or even in lowland areas. At present, *Fagus* stands do not reach the sea level in Italy, differently from northern Europe. By contrast, there is a robust evidence for their presence in coastal lowland areas in previous interglacial periods (Follieri, 1979). In historical times, the presence of *Fagus* is documented in the city of Rome in the "Fagutal Hill". Wood remains of *Fagus* from the site of Longola-Poggiomarino (Heussner et al., 2007; Di Pasquale et al., 2014), 16 m a.s.l., may also prove the presence of beech populations in lowland areas of Campania during the Bronze Age. This site, however, is close to the Vesuvius slopes, which presumably hosted *Fagus* stands and represented a possible source area for these findings.

Corylus was also abundant during this period (Fig. 3). It is likely that hazel mostly benefitted from wet climate conditions, however a human management of its edible fruits may have also influenced the diffusion of the plant. Food waste of hazelnuts has been commonly found in archeological excavations of the Bronze Age in the Campania Plain (Albore Livadie et al., 2011).

Anthropogenic indicators experienced a general decrease in this phase (Figs. 3 and 4). The continuous record of cereal-type pollen is to be related to cultivation. The efficiency of the agricultural system, together with the numerous findings of caryopses from Bronze Age archeological sites, indicate that cereal cultivation was particularly well developed in the Campania Plain, possibly extending also to the coastal area, despite no direct evidence for human settlements. An explanation for the lack of coastal settlements may be that wet climate conditions determined environmental instability and flood events, which seem confirmed by an increase in continental runoff in the Gulf of Gaeta (Margaritelli et al., 2016). The Clanio River was famous since the pre-Roman times for its frequent inundations, which limited the urban development of the area, so that until the 16th century its course was regulated by deep hydraulic works, after which it was named Regi Lagni (Alberico et al., 2017).

Wet climate conditions may also account for a change occurred in the aquatic environment. The increased precipitation probably discharged nutrients in the brackish lagoon inducing a prolonged eutrophic phase, marked by terrific blooms of *Lingulodinium polyedrum* (Fig. 6), a potentially harmful marine dinoflagellate. This species produces colorless spherical spiny cysts, classified as *Lingulodinium machaerophorum* (Deflandre and Cookson) Wall, which are able to fossilize (Kokinos and Anderson, 1995). It is a bioluminescent planktonic organism, commonly living in warm shallow water, where it can be responsible for magnificent displays of phosphorescence phenomena at night along marine coastal environments. *Lingulodinium polyedrum* is a red tide species that has been associated with fish and shellfish mortality events. Deadly red tides have been reported also in the Adriatic Sea, where cell levels reached values of 2×10^7 cells/l (Marasovic, 1989; Bruno et al., 1990). At present, there is no consensus on the direct effects produced by the toxins of this species on human health. *L. polyedrum* has been associated with the production and release of homo-yessotoxin (Paz et al., 2004; Wang, 2008), a dangerous toxin for neuronal cells, whose action site and mechanisms are still unknown. Bruno et al. (1990) reported also the presence of saxotoxin, a toxin able to induce the paralytic shellfish poisoning (PSP), in water samples taken during a bloom of *L. polyedrum*. The PSP may cause high mortality in the exposed population. Thus, it is reasonable to infer that this dinoflagellate may have represented another limiting factor for the establishment of local settlements, being a threat for fishery resources and probably also for human health. The high concentration of this species in this zone (e.g. ca. 210,000 dinocysts/g at 636.5 cm) (Fig. 5), suggests prolonged dangerous water conditions.

The remarkable microcharcoal increase recorded between 4000 and 3600 cal BP may be attributed either to fires produced in local fields around the lagoon or to charcoal produced during volcanic activity of the nearby districts. Charcoal peaks are in good agreement with the age of the Capo Miseno event, obtained from both proximal (3700 ± 500 years; Di Renzo et al., 2011) and offshore (3904 ± 60 cal years BP; Sacchi et al., 2014b) deposits. In any case, the fire activity does not appear correlated with any forest decline.

6.4. 3320–3010 cal BP (595–551 cm)

The pollen diagram profiles a drop in AP percentages, produced by a dramatic increase in Cichorioideae, matching a lithological change from mud to an evaporitic mud, rich in gypsum phenocrysts. This phase reflects a marked change in the depositional environment, probably related to a rapid lowering of the water table, rather than to an opening of the forest. The contemporary high percentages of Cichorioideae and a drop of pollen concentration (Figs. 3 and 5) are likely the result of selective preservation of oxidation-resistant pollen (Bottema, 1975; Havinga, 1984). In addition, the record of *Pseudoschizaea* suggests the incidence of seasonal desiccations (Scott, 1992) and freshwater flows accompanied by erosional processes (Pantaléon-Cano et al., 2003). Erosion and downwash of sediments is confirmed by the record of *Glomus* spores (Kołaczek et al., 2012). In the evaporitic interval, spanning between 5.82 and 5.62 m, almost all the aquatic fauna disappeared from the basin (Sacchi et al., 2014a). In the pollen record only Rivulariaceae seems to be favored by the possible stagnant water of this temporary phase. According to Sacchi et al. (2014a) the lagoon may have experienced a short-lived phase of isolation from the open sea and/or reduced riverine water input. There is presently no evidence of other possible causes (e.g. volcanic activity, or climatic forcing), to explain the environmental change documented in this interval.

6.5. 3010–2450 cal BP (551–451 cm)

The general vegetation conditions are similar to those reported in zone PAT-3 in terms of vegetation structure, being characterized by a forested landscape dominated by broadleaved trees. The main difference regards the floristic composition of the woodlands, which was marked by a clear increase in both deciduous and evergreen *Quercus*, and a decrease in *Fagus*. In addition, the expansion of *Ulmus*, *Carpinus betulus*, and *Ostrya/Carpinus orientalis*, in the upper part of this phase (Figs. 3 and 4), outlines further changes in the composition of the forest communities.

Further insights into the local woodlands come from the pollen record of Lago d'Averno, ca. 11 km far from Lago Patria. Despite the lack of radiocarbon dates, this record (ca. 800 BCE–800 CE) is constrained by historical sources detailing the main environmental changes, which are reflected in both diatom and pollen diagrams (Grüger and Thulin, 1998). The lower part of the Lago d'Averno sequence points to woodlands mostly dominated by *Quercus ilex*, but also rich in deciduous *Quercus*, *Carpinus*, and *Corylus*, with frequencies comparable to Lago

Patria (Figs. 3 and 4). Thus, we can hypothesize a widespread continuous forest, rich in evergreen and deciduous elements, spanning from the lowland coastal areas to the low reliefs of the Phlegraean Fields, with little internal differences in floristic composition, depending on elevation and other site-specific peculiarities. In the coastal sector, this vegetation coincided with the ancient *Silva Gallinaria*, a dense woodland mostly dominated by holm oaks and pines, extending from Lago del Fusaro to the Volturno river mouth (e.g. Biraschi, 1988).

Between 3000 and 2400 cal BP, the pollen record from the Gulf of Gaeta shows a clear vegetation change from forest to open conditions, probably induced by a climate change toward more arid conditions. A general inversion in NAO index polarity (Olsen et al., 2012; Baker et al., 2015) and a decrease in solar activity may have induced a reorganization of the atmospheric circulation in the Mediterranean, possibly leading to a precipitation decrease (Di Rita et al., 2018a, 2018b). A comparable vegetation change is not found at Lago Patria, presumably because local wet conditions preserved local forest ecosystems, except for a temporary forest decline between 2800 and 2600 cal BP (Figs. 3 and 4). This forest decline affected the natural broadleaved vegetation and was coupled with an increase in *Artemisia*, suggesting a drought event. However, a remarkable increase in anthropogenic indicators, notably *Olea*, *Juglans*, *Castanea*, and cereals, clearly indicates that it was related to human activity. In addition, the forest decline matches a microcharcoal peak, possibly linked to man-induced local fires (Fig. 4).

This is a crucial period for the history of human peopling of Lago Patria and surrounding region, culminated with the foundation of important cities, such as Cumae, Capua and Dicearchia/Puteoli, which certainly exerted an impact on the coastal and fluvial ecosystems. The Volturno Plain and Phlegraean Fields were coveted territories for Italic peoples, Etruscans, Greeks, and Romans, thanks to both their strategic positions, within lively fluvial and marine trading routes of the Mediterranean, and the fertility of their volcanic soils. Pollen evidence for increased human impact between 2800 and 2600 cal BP probably refers to the Greek domination of the area, controlled by the close city of Cumae (ca. 10 km from Lago Patria), the first Greek colony on mainland Italy founded, according to Strabo, around 750 BCE. The significant increase in *Juglans* and the first appearance of *Castanea* in this phase may represent the onset of cultivation in Campania (Fig. 4). According to the regional literature, the cultivation of *Castanea* started in Roman time, while the cultivation of *Juglans* is to be referred to a previous period (Russo Ermolli, 2017). At Lago d'Averno, sparse grains of *Castanea* and *Juglans* are probably coeval to our finds, but only the record of *Juglans* was attributed to off-site plantations, possibly located at Cumae that was famous for its orchards (Grüger and Thulin, 1998). Evidence for the pre-Roman cultivation of *Juglans* is also provided by pollen analysis in the Etruscan city of Pontecagnano (Russo Ermolli et al., 2011; Russo Ermolli, 2017). Despite its cultivation, *Castanea* was not widely spread in ancient Campania during the Roman period, whereas it became a common timber in this region starting from the 5th–6th century CE, and represented the dominant wood around 6th–7th century CE, as suggested by anthracological data from Cumae (Di Pasquale et al., 2010). The progressive increase in the use of *Castanea* as hardwood material is clearly reflected in its percentage increase in the Gulf of Gaeta pollen record, suggesting in turn a regional spread of *Castanea* cultivations from Imperial times to lower Middle Ages (Di Rita et al., 2018a). The most interesting finding of *Castanea* in Campania is represented by several fruit shells from edible chestnut in the harbor sediments of Neapolis (end of the 1st century BCE to the 5th century CE), which is the first site documenting systematic chestnut consumption as food throughout the entire Imperial Age (Allevato et al., 2016).

The records of *Olea* and *Vitis* also may have different interpretations. On the one hand, their occurrence during the local domination of Greeks and Etruscans, which knew olive and grape exploitation, suggests local cultivation. On the other hand, their increase, still accompanied by two main natural companion plants, respectively *Quercus ilex* and *Alnus*, may point to the development of natural populations (Fig. 3). Despite the common suggestion that a massive cultivation of *Olea* in Campania was already diffused during Greek and Roman times, paleobotanical evidence supporting this assumption is still lacking. *Olea* is present in low frequencies in the pollen records of Salerno, Averno, Neapolis and Paestum and it is always associated with other evergreen elements of the Mediterranean maquis (Russo Ermolli, 2017 and references therein). At Lago Patria, *Olea* starts increasing at ca. 3200 cal BP, when its cultivation seems unlikely. It shows a further increase between 2800 and 2600 cal BP, in correspondence with the development of Cumae, which may be consistent with local management and cultivation of olive trees by Greeks, not excluding the domestication of local plants from natural woodlands. Also the increase in *Vitis*, between 2600 and 2450 cal BP, may be related to wild grapes management and cultivation by Greeks and/or Etruscans, although these people likely introduced and planted in Italy also varieties originated from other region of the Mediterranean and the Near East (Zecca et al., 2010; Wales et al., 2016; Terral et al., 2010). At that time, the cultivation of *Vitis* was practiced in many sites of the central Mediterranean, including Campania. The pollen evidence from the Etruscan site of Pontecagnano, in the Sele River plain, suggests the exploitation of the cultivated subspecies of grape (*Vitis vinifera* subsp. *vinifera*) in Campania since at least the 6th century BCE, although analyses on grape macro-remains found in the site of Longola-Poggiomarino may predate the cultivation of this subspecies to the Early Bronze Age.

Local human people probably played a role also in the development of *Pinus*, recorded in the same time-interval. Unfortunately, no clear evidence is available for pine plantation to date, although waterlogged plant remains from the Neapolis harbor indicate that *Pinus pinea* was planted in that area since at least the 2nd century BCE, as a result of well-developed arboricultural practices (Allevato et al., 2016). Its timber was used in shipbuilding and its cones as stoppers for amphorae. It is also possible that *Pinus* pollen partly originated from natural pine populations in the sandy coastal belt within the ancient *Silva Gallinaria*.

The aquatic environment of Lago Patria was characterized by high frequencies of Rivulariaceae and *Lingulodinium*, along with an increase in both *Spiniferites* and foraminiferal linings, still suggesting brackish, eutrophic water conditions (Fig. 3).

6.6. 2450–2230 cal BP (451–405 cm)

A remarkable forest decline corresponds to a drop of broadleaved trees and an expansion of Amaranthaceae/Chenopodiaceae (Figs. 3 and 4). This vegetation change, reflected also in the pollen concentration diagram (Figs. 3 and 5), is not present in other pollen records of the Campania region. In the Gulf of Gaeta, this time-interval is characterized by forest development, while a slight forest decline is recorded between 2200 and 2000 cal BP (Di Rita et al., 2018a). At Lago d'Averno a sudden drop of arboreal vegetation was related to the cutting of a dense woodland in 37 BCE, as documented by both Strabo and Virgil (Grüger and Thulin, 1998). Forest depletion was produced also in the *Silva Gallinaria* in the second half of the 1st century BCE by the Roman general Sextus Pompey for the building of its naval fleet, but our pollen sequence does not record this event. Evidence for forest decline around 2000 cal BP is also found in several coastal sites of central and southern Italy, as a result of a progressive forest degradation, mainly induced by human activities during the Roman domination (Di Rita and Magri, 2012).

At Lago Patria, local people likely produced a large clearance of the lowland forest surrounding the lake, coincident with the *Silva Gallinaria*, before the development of the close Roman colonies of Liternum, Volturnum and Puteoli, founded at the beginning of the 2nd century BCE. Our age-depth model does not allow ascribing this vegetation change to the settlers of Liternum, built in 194 BCE on the southern

bank of the ancient *Literna palus*. However, the forest decline may reflect the human impact at the beginning of the Roman domination of the Campania region since the 4th century BCE, following the Latin and Samnite wars. Cumae and Capua, were proclaimed by Romans *civitas sine suffragio* in 334 BCE and 338 BCE, respectively, a special level of citizenship in the Roman Republic, usually awarded to conquered cities at the beginning of the Roman domination. The estuarine coastal area around Lago Patria, was part of the so-called *Campania Felix*. A territory particularly renowned for the quality of its agricultural products, especially olive oil, wine and wheat, whose production was enhanced in this phase, as shown by the increase in *Olea*, *Vitis* and cereal-type at the end of this period. The continuous records of *Juglans* and *Castanea*, showing values comparable to those from the Gulf of Gaeta, confirm their regional cultivation in Roman times (Fig. 3). In this phase, there is also the first occurrence of Cannabaceae, probably related to the onset of hemp cultivation.

A rapid, major increase in Amaranthaceae/Chenopodiaceae may reflect the development of halophilic plant communities along Lago Patria lakeshore, due to either natural causes (e.g. sea water input variability) or to the use of the brackish lake waters for salt extraction. Salt-works were distributed in several wetlands during Roman times, especially around important estuarine areas of Italy (Morelli et al., 2004; Arnoldus-Huyzendveld and Citter, 2008), and the environmental changes produced by their establishment can be often detected in pollen records (Di Rita et al., 2010; Bellotti et al., 2011). At Lago Patria, archeological evidence and historical documents do not support the existence of local salt-works, which were conversely well documented during Roman times in the Herculaneum area, 30 km south of Lago Patria. Another possible interpretation for the increase in Amaranthaceae/Chenopodiaceae is the growth of pioneer weed, such as *Chenopodium album*, competing with local crops.

The record of *Spiniferites* and foraminiferal linings indicate brackish water conditions while the remarkable increase in Rivulariaceae suggests a new process of eutrophication (Figs. 3 and 5).

6.7. 18th and 19th century BCE (ca. 140–180 cal BP; 232–365.5 cm)

After a sedimentary hiatus lasted from 2230 to 180 cal BP (1770–1820 CE), the pollen record shows an open landscape featured by plants indicating intense agricultural and sylvicultural activities (Figs. 3 and 4). The coastal forest ecosystem between 4870 to 2230 cal BP was almost completely lost, likely because of a strong impact of human activity.

This period corresponds to the Bourbon domination when the area was included in the Kingdom of Naples. The major reclamation works of the Regi Lagni and Volturno delta plain that started from the end of the XVI century during the Spanish viceroyalty were continued by the Bourbons, in order to obtain new farming land, reduce flood risk and improve public health (Ruberti et al., 2017; Ruberti and Vigliotti, 2017). The lithostratigraphic unit of this interval is partly composed of manreworked material used for the construction of Lago Patria embankments since the Bourbon land reclamation works of the 18th century (Sacchi et al., 2014a).

The main herbaceous crops were represented by Cannabaceae and cereals, among which it stands out the cultivation of *Zea mays* (corn) as human and animal food (Fig. 3). The increase in Fabaceae likely reflects forage cultivation. This area of the Campania plain is historically involved in the buffalo rearing to produce the worldwide famous *mozzarella di bufala* cheese, a resource that during the Bourbon domination experienced a first phase of industrial exploitation. Meadows disturbed by pastures and other farming activities were characterized by *Plantago* and *Polygonum aviculare* type (Fig. 3). A major increase in Amaranthaceae/Chenopodiaceae may indicate the development of halo-nitrophilous communities related both to agriculture and water salinity (Figs. 3 and 5). An increase in Brassicaceae may reflect cultivation of *Brassica* species, mostly cabbage varieties, common since the Roman times in Campania (Russo Ermolli et al., 2014).

Sylvicultural activities were carried out in inland areas and mainly addressed to *Olea*, *Vitis*, *Juglans* and *Castanea* (Fig. 3). Probably, also pollen of *Corylus* was partly originated from regional hazelnut cultivations, which are particularly abundant in the nearby province of Avellino, whose name is linked to *Corylus avellana*. In the present landscape of the Campania Plain, mixed orchards frequently include all the abovementioned trees.

The indicators of the aquatic environment point to a brackish swamp bordered by sedges and reed communities, as indicated by the increase in foraminiferal linings, Cyperaceae and *Sparganium*/*Typha* and *Typha latifolia* (Fig. 3).

7. Conclusions

The pollen record from Lago Patria contributes to fill a gap of knowledge on the paleoenvironmental changes of the coastal sector of the Campania Plain during the time-interval 4800 to 2200 BP. The first phase of this period was characterized by major explosive volcanic eruptions, which had a deep impact on the Bronze Age human peopling of the region. A second phase, after 2800 BP, was featured by the local domination of the coastal area by Greeks, Etruscans, and Romans. The top of the pollen record, interrupted by a sedimentation hiatus between 2200 and 180 cal BP, shows the environmental conditions occurred during the Bourbon domination.

Our pollen record leads to the following conclusions:

- The Lago Patria area was surrounded by a mixed deciduous and evergreen oak-dominated lowland forest, rich in both xeric and mesic woody taxa. This forest type, whose remnants in coastal natural parks represent valuable biodiversity hot-spots, was widespread along the Tyrrhenian coast of Italy since the early Holocene. Afterwards, it experienced a progressive fragmentation and decay due to both climate and human impact, especially in the late Holocene, as also evidenced at Lago Patria.
- Significant pollen frequencies of montane mesophilous trees, such as *Fagus* and *Abies*, point to the presence of beech and fir populations at lower elevation than at present, in agreement with the regional paleobotanical evidence.
- Clear forest fluctuations attributable to climate changes, human impact, and their interplay are mostly recorded by broadleaved trees, which represent the dominant floristic elements of the forest cover. Anthropogenic indicators are continuously recorded, in contrast to the evidence of the few ephemeral archeological sites found in the area up to Greek and Roman times. This evidence on the one hand stimulates new archeological investigations on local coastal areas, and on the other hand drives us to consider local environmental factors of inhospitality. Among these latter there are unstable and unhealthy conditions determined by historically documented malaria diseases and floods produced by the Clanio and Volturno Rivers. Our data add a possible new cause of inhospitality represented by harmful lagoon waters affected by algal blooms of *Lingulodinium polyedrum*, a dinoflagellate potentially dangerous for fishery and human health.
- Pollen and NPPs assemblages of aquatic organisms point to a clear change from freshwater conditions, populated by *Myriophyllum* spp., *Pediastrum*, and *Filinia* rotifers, to brackish conditions, featured by the presence of foraminifers, salt-tolerant dinoflagellates, and *Ruppia*. This process is consistent with the change from a back-barrier environment with cat's eye freshwater ponds to an open brackish lagoon, recorded by the malacological analysis carried out in the same core.
- Climate played a major role in the forest cover and community composition. In particular, a decline in broadleaved taxa, culminating around 4200 cal BP, seems related to the 4.2 ka arid climate event. An increase in anthropogenic indicators after the maximum opening of the forest at 4200 cal BP, accompanied by significant

microcharcoal concentrations, suggest that human populations benefited from a natural vegetation opening to develop agro-pastoral activities and used fire to clear woodlands and obtain new land for cultivation. A new increase in wet conditions was recorded between 3900 and 3300 BP, testified by a remarkable development of mesic trees, notably *Fagus*, whose populations established in hilly and probably lowland areas of the region. This phase corresponds to a period of continental runoff related to increased precipitations as reconstructed from the Gulf of Gaeta. An apparent forest opening between 3300 and 3000 BP can be interpreted as the effect of a lowering and desiccation of the lake, leading to the formation of evaporitic gypsum deposits, sediment erosion and selective preservation of local resistant herbaceous pollen types, although no evidence currently allows us to attribute this environmental change to any known natural or man-induced event. The period between 3000 and 2200 cal BP points to general wet climate conditions, probably warmer than the previous ones, as indicated by a further slight development of evergreen *Quercus* and *Olea*. The temporary decline of broadleaved communities, recorded between 2800 and 2600 cal BP, seems mostly attributable to the foundation of the Greek city of Cumae, although it coincides with a still under-investigated climate event leading to more arid conditions in southern Italy. The Bourbon period at the top of the record is characterized by open vegetation dominated by cultivations and pasturelands.

- The present work adds new information on the regional exploitation of important economic plants, such as *Vitis*, *Olea*, *Juglans*, *Castanea* and cereals among others. Cereals represent the main cultivation all along the sequence, in agreement with the archeological and paleobotanical evidence indicating their regional production since the middle Holocene. *Olea* and *Vitis*, present all along the pollen record, were probably managed in Campania during the Bronze Age, as pointed by numerous finds in archeological sites. The increase in *Olea* and *Vitis* in our pollen record starting from the 8th and 6th century, respectively, is consistent with the onset of their cultivations by Greeks and Etruscans, although an increase in their wild companion species also suggests the development of wild populations within their natural woodlands. The pollen record of *Juglans* confirms its cultivation by the Greeks, but scattered pollen grains during the Bronze Age point to wild walnut populations still doubtfully interested by human management. Wild trees of *Corylus* were certainly foraged by Bronze Age human populations. The development of *Corylus* around 3700 cal BP, accompanied by other paleobotanical finds, indicates that wild hazel trees were a major regional resource for food and timber, as it is today in Campania. *Castanea* shows an almost continuous record since the 8th century BP, probably in relation to the onset of local exploitation. The Bourbon period shows an intensification of the cultivations, with main herbaceous crops represented by Cannabaceae and cereals, including *Zea mays*. In this period, Brassicaceae may reflect cultivation of *Brassica* species, while Fabaceae likely points to forage cultivation for animals, likely involved in the production of the local *Mozzarella di Bufala*.

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